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REDUCTION in BEARING SIZE due to SUPERCONDUCTORS in MAGNETIC BEARINGS

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Overview

This presentation assesses a design concept that reduces the size of magnetic bearings. The small size will enable magnetic bearings to fit into limited available bearing volume of cryogenic machinery.

The design concept, called SUPERC, uses (high Tc) superconductors or high-purity aluminum conductors in windings instead of copper. The relatively high-current density of these conductors reduces the slot radial thickness for windings, which reduces the size of the bearings.

MTI developed a sizing program called SUPERC that translates the high-current density of these conductors into smaller sized bearings. We used this program to size a superconducting bearing to carry a 500-lb load. The sizes of magnetic bearings needed by various design concepts are as follows:

- SUPERC design concept = 3.75 in.
- Magnet-bias design concept = 5.25 in. [2]
- All electromagnet design concept = 7.0 in. [2]

These results indicate that the SUPERC design concept can significantly reduce the size of the bearing. This reduction, in turn, reduces the weight and yields a lighter bearing. Since the superconductors have inherently near-zero resistance, they are also expected to save power needed for operation considerably.

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OVERVIEW

Objective: *Assess a Concept to Reduce the Size of Magnetic Bearings*

Design Concept

- Utilize High-Current Density of Hyperconductors or Superconductors to Reduce Size

Accomplishments

- Computer Program SUPERC Developed to Size Superconducting Bearings and Controls

- 500-lb Magnetic Bearing Sized Per Various Concepts:
    - SUPERC Design Concept = 3.75 in.
    - Magnetic Bias Design Concept = 5.25 in.
    - All Electromagnet Design Concept = 7.0 in.

Superconducting Bearings Are Smaller and, Hence, Suitable for Cryogenic Aerospace Applications

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Approaches to Long-Life Cryogenic Bearings

Currently, rolling element bearings are being used to support rotors in high-performance cryogenic turbopumps such as the SSME. The life of these bearings is limited due to wear under high-load conditions. Hence, there is a need to remove the contact/wear environment in cryogenic rotor support systems.

The options to remove the wear environments are fluid film and magnetic suspension. The challenge to both technologies is to achieve the required load capacity within limited available volume with least power consumption.

We selected to study the magnetic bearing option because it can meet load requirements without any physical contact. The fluid-film bearing, on the other hand, needs contact by fluids. Its performance is sensitive to the lubrication capability of cryogenic fluids, which is known to be low at cryogenic temperatures.

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APPROACHES TO LONG-LIFE CRYOGENIC BEARINGS

- Rolling Element Bearings — Life Limited Due to Wear

- Remove Contact/Wear Environment

- Options:
  - Fluid Film
  - Magnetic

- Challenge — Achieve Required Load Capacity in
  - Limited Available Volume
  - Least Power Consumption

- Selected Magnetic Bearings
  - No Solid or Fluid Contact Required
  - Lower Power Dissipation

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The Problem

Magnetic bearings are fundamentally limited by the magnetic, electric, and mechanical strength of materials used. The mechanism by which magnetic strength (flux density) limits the load capacity is well understood [2]. The mechanism by which the electric strength (current density) limits the size of the bearing is not very well understood. The challenge is therefore to understand how current density controls the size of the bearing.
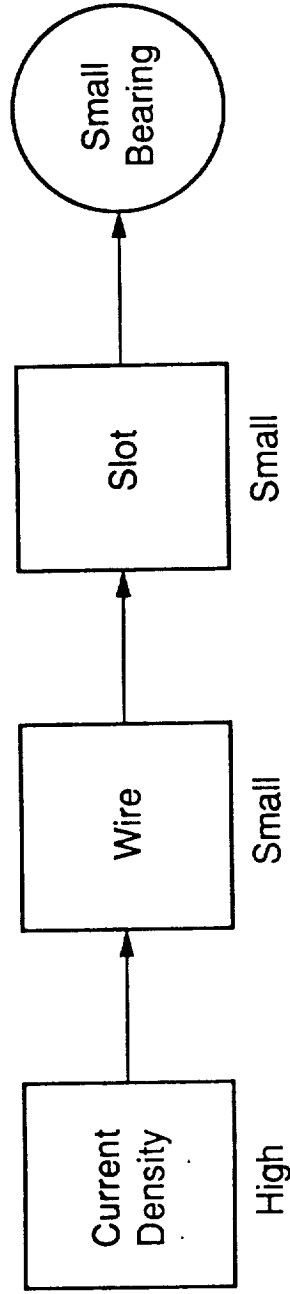
The Solution

The SUPERC design concept consists of replacing copper winding (present in conventional magnetic bearings) by hyperconducting or superconducting windings. These conductors are known to carry currents at densities one or two orders of magnitude higher than that of copper (1000 A/mm^2 vs. 10 A/mm^2).

The higher current density reduces the size of wire to carry the same ampere turns. The smaller wire requires a smaller slot. By reducing the radial thickness of the slot by an order of magnitude, the SUPERC design concept reduces the size of the bearing.

Alternatively, the magnet bias design concept [6, 7] saves the size by replacing the volume occupied by bias currents with that of permanent magnets. As per [6], the resulting bearing is smaller as the electromagnet coil window is smaller because coils are sized to carry control currents only.

THE PROBLEM

The Problem: Understand How Higher Current Density Reduces Bearing Size

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┌──────────┐      ┌──────┐      ┌──────┐         ╭──────────╮
│ Current  │ ───► │ Wire │ ───► │ Slot │ ───►    │  Small   │
│ Density  │      │      │      │      │         │ Bearing  │
└──────────┘      └──────┘      └──────┘         ╰──────────╯
    High            Small          Small
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The Solution: SUPERC Design Concept. High Current Density Leads to Smaller Wire, Smaller Slot, and Hence Smaller Bearing

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Operating Principle of SUPERC Design Concept

The SUPERC design concept [5] consists of a ferromagnetic journal mounted on a shaft which is attracted by controlled electromagnets in the housing. If the forces due to operation of a machine causes the rotor to move up, the current in the top electromagnet is decreased to reduce the upward attraction force.

The servo system that regulates the current consists of a sensor, controller, and power amplifier. The sensor converts the mechanical position of the rotor into an electrical voltage signal. The controller converts this sensor signal into a control signal that can stabilize the rotor. The power amplifier converts the control signal into control currents that drive the electromagnets.

The housing is sized to carry iron, windings, and sensors. The iron is needed to channel flux, and its size is dictated by the flux saturation. The windings energize the electromagnets, and its size is dictated by current density needed to generate the required ampere turns.

[The weight of electronics needed to generate bias currents could be saved by using persistent currents.]

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ACTIVE SUPERCONDUCTING BEARING CONCEPT

Superconductor
Windings

B

A

Iron

Journal

O

Stator

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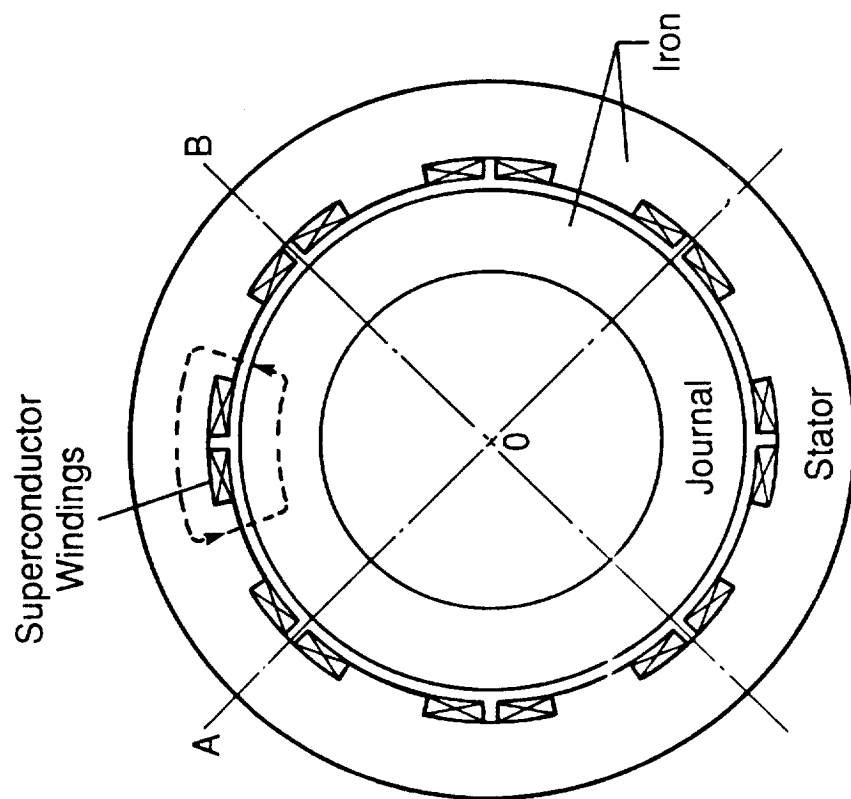
Sizing Analysis

The bearing diameter, D, is estimated by the formula:

$$D = d + 2g + 2t_j + 2t_r + 2t_s \qquad (1)$$

where the shaft diameter, d, and the magnetic gap, g, are fixed by application. The radial thickness of the journal, return path, and slot (t_j, t_r, t_s) are estimated as follows:

Iron Area (Magnetic Path)

- Estimate the total pole area, A, needed to equalize the mechanical pressure due to given force, P, with the saturation pressure $B^2/2 \mu_o$ that can saturate the magnetic material.

- Estimate the individual pole width, b_p, from the total pole area, A, number of poles, n, and axial flux length, L.

- Estimate the thickness of journal and return paths by assuming that all cross sections normal to flux paths have an area equal to individual pole area, so that $t_j = t_r = b_p$.

Winding Area (Electric Path)

- Estimate the ampere turn, NI, needed to generate the flux density, B, in the magnetic gap from the magnetic circuit analysis.

- Compute the winding area, A´, needed to generate this ampere turn, NI, from a conductor of current density, J, and fill factor, J´.

- Estimate the slot width, b_s, as the difference between the pole pitch and pole width, b_p.

- Estimate the slot thickness, t_s, from the total winding area divided by the slot width.

SIZING ANALYSIS

Superconductor
Windings

B_p

t_s

B

A

g

l

l

d/2

O
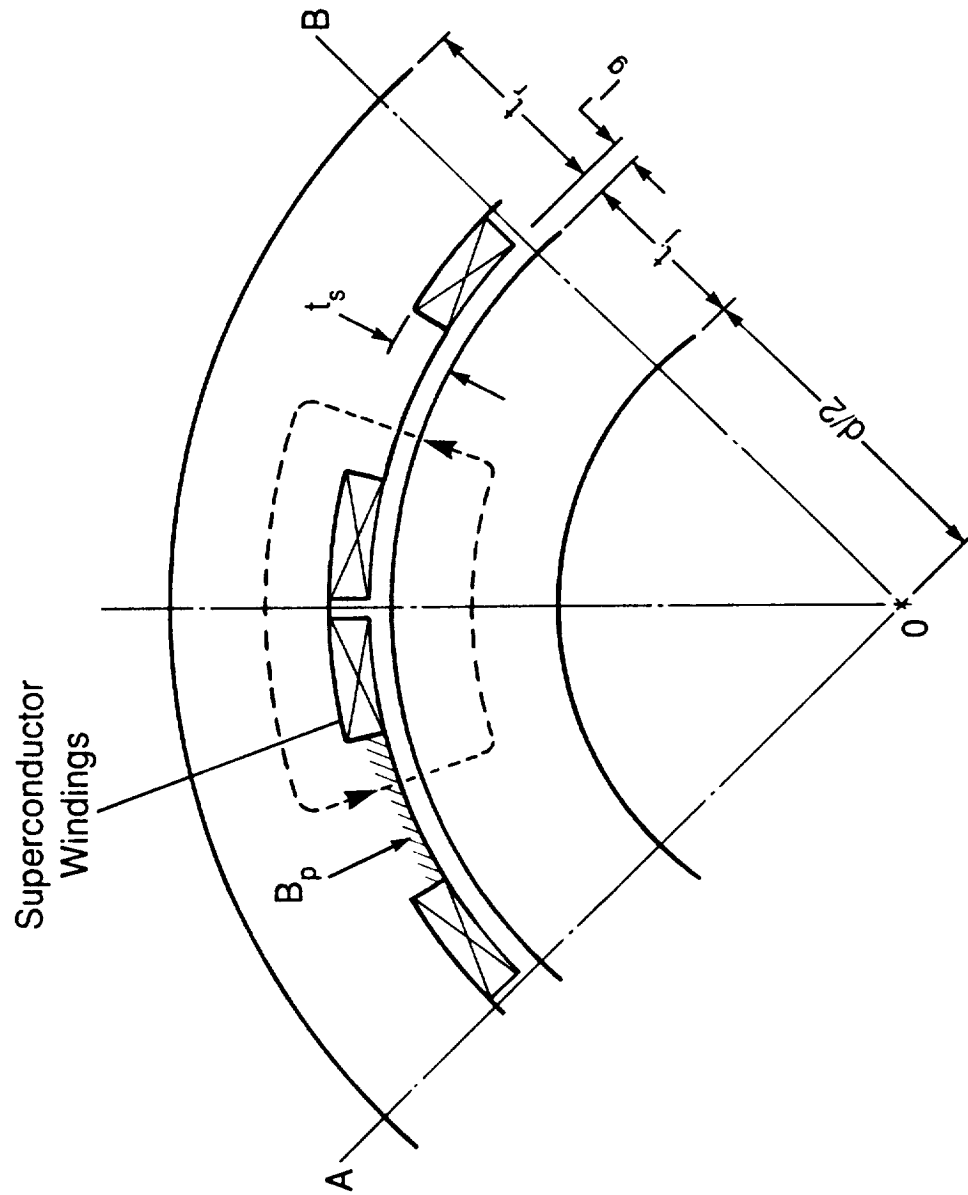
Computer Program to Size SUPERC Bearings

The program sizes the bearing housing as well as the control system from given load requirements and B-H curve of flux path material.

The program outputs include geometric, dynamic, thermal, and electric variables. Sample parameters outputted are:

Geometric	Dynamic	Thermal	Electrical
Housing Diameter	Shaft Orbits	Temperature Rise	Currents
Pole Dimensions	Stiffness	Heat Generated	Inductance
Slot Dimensions	Damping		Resistance
Journal Dimensions	Mass		Back emf

In addition, the program allows for several secondary effects such as core reluctance, leakage flux, fringe flux, lamination thickness, pole angle, and temperature coefficient of resistance. These effects combine to degrade the load capacity considerably and, hence, are needed for accurate sizing.

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COMPUTER PROGRAM TO SIZE SUPERCONDUCTING BEARINGS

Input: Load, Flux Density, Current Density

Output: • Geometric

• Dynamic

• Thermal

• Electrical

• Control System

Included Secondary Effects

• Core Reluctance

• Leakage Flux

• Fringe Flux

• Lamination Thickness

• Pole Angles

• Temperature Coefficient of Resistance

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Estimated Performance Parameters

In addition to sizing, the program estimates the performance capability of the bearing by a set of seven parameters:

System

Bearing Size
Bearing Weight
Power Loss

Load

Magnetic Pressure
Load Capacity (Static)
Load Capacity (Dynamic)
Load Efficiency

The bearing size is quantified by the outer diameter of the housing. The bearing weight includes that of the housing and journal, but excludes that of the support electronics. The power loss is estimated from ohmic losses in the windings.

The magnetic pressure is defined as $B^2/2 \mu_o$. The static load capacity is computed as the output force per unit projected area of the bearing. The dynamic load capacity is computed as the dynamic load transmitted to the housing for specified shaft orbital amplitude at specified speed.

The load efficiency is computed as the ratio of output force (lb) and the weight of the bearing needed to generate this force. This output force is computed as maximum force that can be generated along a single axis.

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ESTIMATED PERFORMANCE PARAMETERS

Bearing

- Size
- Weight
- Power

Load

- Magnetic Pressure
- Load Capacity (Static)
- Load Capacity (Dynamic)
- Load Efficiency

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Performance Comparison

Based on the analysis, the performance of a 500-lb magnetic bearing are compared to the following design approaches:

- SUPERC
- Magnet bias
- All electromagnet

The following parameters are kept constant as a basis for comparison:

- Radial load: 500 lb (2230 N)
- Shaft diameter: 2 in. (50.8 mm)
- Journal diameter: 3 in. (76.2 mm)
- Flux density limit: 1.6 tesla
- Axial length of flux: 4.3 in. (109 mm)

A 24-pole design with a current density of 100 A/mm^2 was used in the SUPERC design concept.

This table indicates that the SUPERC design concept yields bearings that are smaller in size, lighter in weight, and delivers higher load (lb) per each pound of bearing weight.

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PERFORMANCE COMPARISON OF
MAGNETIC BEARING DESIGN CONCEPT

Performance Parameter	Design Concept		
	SUPERC	Magnet Bias	All Electromagnet (Vandium Permendur)
Load Capacity Per Axis (lb)	500	500	500
Journal Diameter (in.)	3	3	3
Axial Flux Path Length (in.)	4.3	4.3	4.3
Size/Outer Diameter (in.)	3.75	5.25	7.0
Weight/Stator and Journal (lb)	9.5	21.4	43.8
Load Efficiency (lb/lb)	52.6	23.4	11.4
Remarks	• Smaller Size • Lighter Weight	• Medium Size • Medium Weight	• Large Size • Large Weight

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Size Comparison

To give a physical feel for the bearing size, the accompanying figure compares the actual size of the bearing per various design concepts.
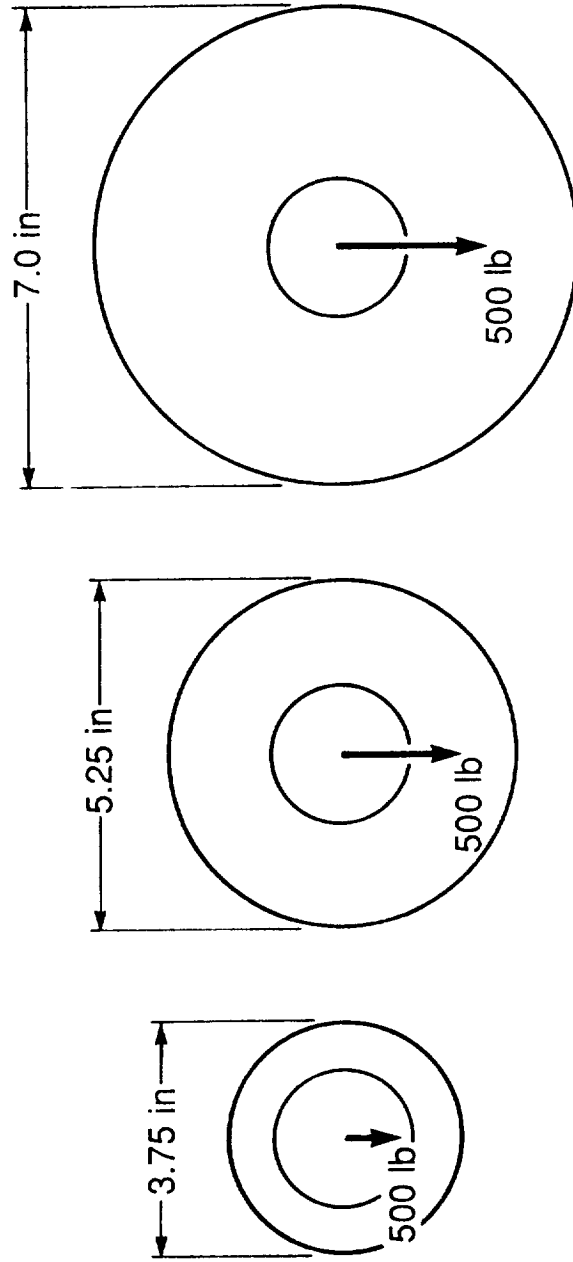
The SUPERC bearing is half the size of all electromagnetic (vanadium permendur) designs. It is 30% smaller than the magnet bias bearing. This small size is due to the higher current density which reduces the slot size and, hence, needs smaller sized electromagnets.

The SUPERC bearing is about 4.6 times lighter than all electromagnetic (vanadium permendur) designs and about 2.2 times lighter than magnet bias design. The lighter weight is attributed to the reduced size afforded by higher current densities.

For the same lb of bearing, the SUPERC design can carry a load that is double that of the magnet bias design and four times that of all electromagnetic designs.

These numbers indicate that introduction of superconductors can substantially improve the performance of the magnetic bearings.

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SIZE COMPARISON

7.0 in

500 lb

**All Electromagnet
Design Concept [3]**

5.25 in

500 lb

**Magnet Bias
Design Concept [2]**

3.75 in

500 lb

**SUPERC
Design Concept [1]**

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Effect of Current Density on Size Reduction

The minimal housing diameter needed for a 500-lb bearing with a 3-in. diameter journal is calculated as per the preceding analysis for various current densities. This analysis yields the following size reduction table:
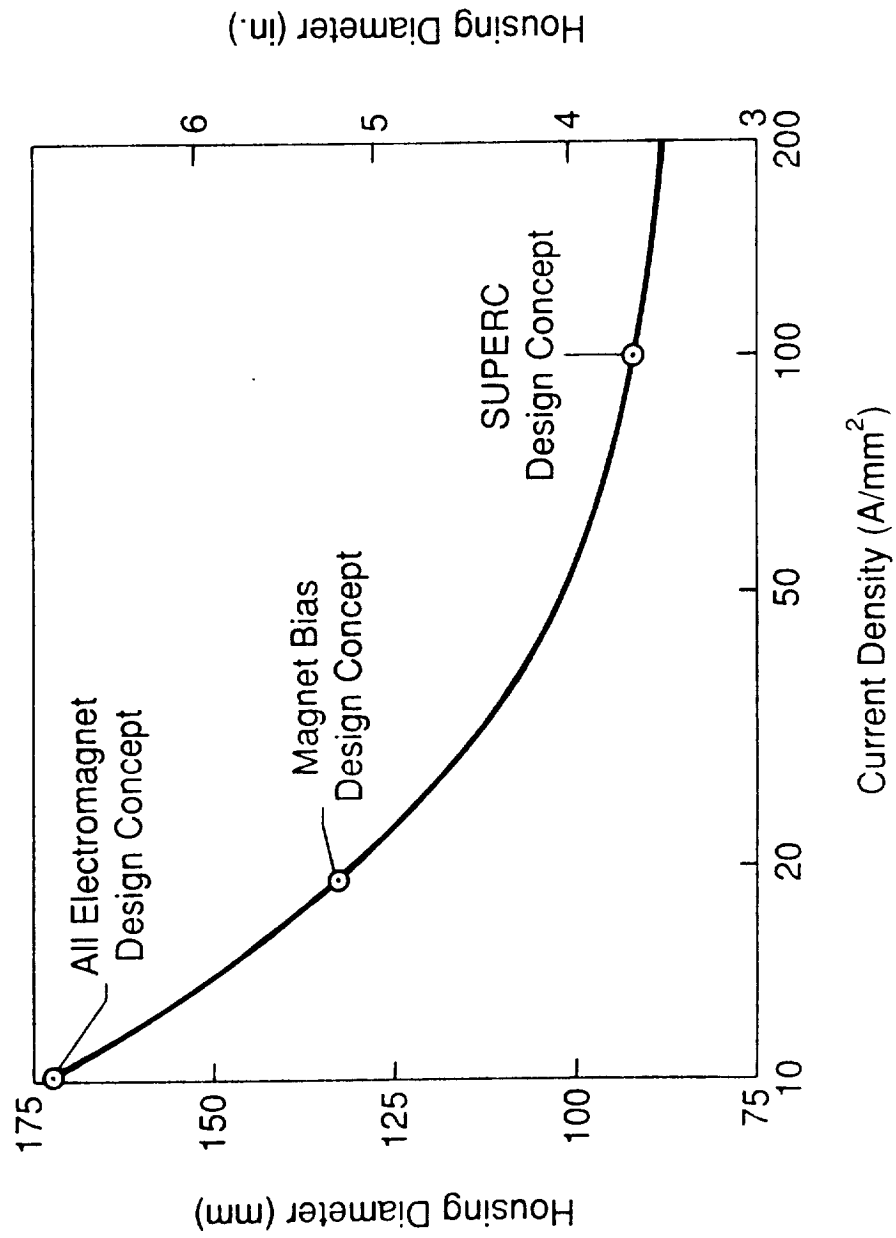
	Current Density (A/mm^2)	Multiplier	Minimal Housing Diameter (mm)	% Reduction
Copper	10	×1	172	--
	20	×2	128	25
	50	×5	101	41
	100	×10	93	46
Superconductor	200	×20	88	49

From the current density vs housing diameter plot, it is clear that the payoff of current density (size reduction) is initially high when the current density is increased by a factor of 2 to 5 (from 10 to 50 A/mm^2). Further increase in current density does not automatically payoff as a proportional size reduction. Beyond 200 A/mm^2, the current density does not have any appreciable payoff.

The magnet bias design equals the performance of SUPERC bearings at a current density of 20 A/mm^2. A current density of 50 A/mm^2 would then result in a bearing better than the magnet bias design.

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EFFECT OF CURRENT DENSITY ON SIZE REDUCTION

Housing Diameter (in.)

Housing Diameter (mm)

Current Density (A/mm^2)

All Electromagnet
Design Concept

Magnet Bias
Design Concept

SUPERC
Design Concept

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CONCLUSIONS

- The Analysis Presented Herein Indicates That the SUPERC Concept, Which Utilizes Superconductors, Can Reduce the Size of Magnetic Bearings by As Much As 30% Compared to the Most Recent Magnet Bias Design Concept.

- It Can Also Carry Double the Load Per lb of Bearing Weight.

- These Results Indicate That the SUPERC Design Concept Is Attractive As a Small-Size, High-Load Bearing for Cryogenic Turbomachines in Aerospace Applications.

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REFERENCES

1. Rao, D. K. and J. F. Dill. "Identification of Potential Candidates for Superconducting Bearings in SDI Systems." MTI Technical Report 90TR28, prepared for SDIO, May 1990.

2. Meeks, C., E. DiRusso, and G. V. Brown. "Development of a Compact, Lightweight Magnetic Bearing." Presented at the 26th Annual AIAA/SAE/ASME/ASEE Joint Propulsion Conference in Orlando, Florida, July 16-18, 1990.

3. Anonymous. "Magnetic Bearings Catalog Data Sheet." MBI, Redford, Virginia.

4. Rao, D. K. and J. F. Dill. "Comparative Assessment of Single-Axis Force Generation for Superconducting Suspensions." Presented at the 25th IECEC Conference, Reno, Nevada, August 1990.

5. Dill, J. F., D. K. Rao, and R. Decher. "A Feasibility Study for the Application of High-Temperature Superconducting Bearings in Rocket Engine Turbopumps." Presented at the 1990 Conference on Advanced Earth-to-Orbit Propulsion Technology, Huntsville, Alabama, March 15-17, 1990.

6. Meeks, C., S. D. Schwartz, V. Spencer, and A. Kascak. "Design of a Highly Efficient Magnetic Bearing for Cryogenic Applications." Presented at the 1990 Conference on Advanced Earth-to-Orbit Propulsion Technology, Huntsville, Alabama, May 15-17, 1990.

7. McCarty, L. H. "Hybrid Design Lightens Magnetic Bearing." Design News, vol. 46, no. 11, pp 156-157, June 11, 1990.

8. Haberman, H. and G. L. Liard. "An Active Magnetic Bearing System." Tribology International, vol. 13, no. 2, pp 85-89, April 1980.

9. Maslen, E., P. Hermann, M. Scott, and R. R. Humphris. "Practical Limits to Performance of Magnetic Bearings: Force, Slew Rate, and Power Requirements." Presented in Magnetic Bearing Technology Workshop, NASA Langley Research Center, Hampton, Virginia, February 1988.

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